Effects of FES-Ambulation Training on Locomotor Function and Health-Related Quality of Life in Individuals With Spinal Cord Injury

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Background: The combination of body weight-supported gait training with functional electrical stimulation (FES) may provide the optimal stimulus for improving overground walking after spinal cord injury (SCI). This potential benefit is likely due to the combination of specificity with the maximization of muscle contractions. **Objectives:** To investigate the effects of 12 weeks of FES-ambulation on overground walking and health-related quality of life (HRQOL) in individuals with SCI. **Methods:** Six individuals (60.5 ± 13.2 years) with SCI (C4-L3; AIS D; 9.3 ± 12.0 years post injury), completed a thrice-weekly, 12-week FES-ambulation training program. Locomotor function was assessed via the Walking Index for Spinal Cord Injury II (WISCI II), the 6-minute walk test (6MWT), the 10-meter walk test (10MWT), and the body-weight support required during training. HRQOL was assessed via the Short Form-36, the Perceived Stress Scale, and the Center of Epidemiological Studies for Depression scale. **Results:** Participants showed significant improvements in the 6MWT (223.6 ± 141.5 m to 297.3 ± 164.5 m; $P = .03$), the required body weight support (55.3% ± 12.6% to 14.7% ± 23.2%; $P = .03$), and a nonsignificant trend toward an increase in walking speed during the 10MWT (0.69 ± 0.4 m/s to 0.9 ± 0.5 m/s; $P = .08$) following the training program. Four participants showed improvements on the WISCI II (1-4 points). Participants also showed a decrease in the Short Form-36 pain score (6.5 ± 1.2 to 5.0 ± 1.7; $P = .04$) and an increase in the overall mental health score (47.8 ± 12.6 to 54.2 ± 6.7; $P = .04$). **Conclusion:** FES-ambulation was associated with enhanced overground walking in individuals with AIS D SCI, reduced pain, and improved mental health. **Key words:** *body weight support, electrical stimulation, overground walking, pain, psychological well-being, rehabilitation*

Improving walking ability is a high priority for individuals with incomplete spinal cord injury (SCI),[1,2] which highlights the importance of improving methods of locomotor rehabilitation. Diminished ambulatory capacity after SCI can significantly reduce an individual's independence, as it becomes difficult to perform activities of daily living. Furthermore, reduced independence and physical function can translate into a decreased quality of life (QOL). To date, there is a growing body of evidence that supports the positive effects that body weight-supported treadmill training (BWSTT) have on locomotor function in individuals with American Spinal Injury Association Impairment Scale (AIS) C and D injuries.[3-6] These benefits include improved overground locomotor function, which has been shown after short-term[7] and long-term investigations,[4] and enhanced perceived physical function and QOL.[4,8,9]

Although BWSTT has proven to be an effective means for improving locomotor function in individuals with incomplete SCI, it has rehabilitative and clinical limitations. First, as this form of therapy most commonly utilizes manual assistance throughout the gait cycle from therapists (or robotic assistance from a Lokomat), the exercise can be partially passive for the participant. This is certainly true for persons with little to no ambulatory capacity, but it is also true for many of those who are more capable walkers (if the legs fatigue during a session, then more assistance is required). Also, physical therapy methods that rely on external assistance may cause the participant to

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Table 1. Participant characteristics

Participant	Age	Gender	Neurological level	AIS	Years post injury
1	70-75	Male	L4	D	1-5
2	70-75	Female	T6	D	1-5
3	55-60	Female	L3	D	1-5
4	60-66	Male	C5	D	1-5
5	50-55	Female	C5	D	20-30
6	35-40	Male	C5	D	15-20

Note: AIS = American Spinal Injury Association Impairment Scale.

fight the assistance or become less active, thereby limiting any potential training effects.[10] In addition to these rehabilitative limitations, BWSTT is very physically demanding on the individuals assisting with the stepping, and thus the duration and quality of gait training may be compromised.[11] Likewise, functional electrical stimulation (FES)-*cycling* engages the leg muscles and has been shown to increase muscle strength and improve muscle morphology after SCI[12-14]; however, this form of therapy is not gait specific and therefore may not be optimal for improving locomotor function in individuals with neuromuscular dysfunctions.

Accordingly, FES-*ambulation* therapy has recently emerged as a particularly promising mode of exercise rehabilitation. As it is gait specific and optimizes lower limb muscle contractions, it may provide more effective ambulation therapy for individuals with SCI. To expand, it is likely that these putative improvements in walking offered by FES-ambulation are due to both muscle strengthening and improved timing and coordination of muscle contractions. It is important to note that the FES-ambulation used in the current study is not as gait specific as treadmill training due to the elliptical movement of the legs. However, it is also more gait specific than a typical elliptical machine, as the footplates are programmed to provide plantar flexion and dorsiflexion in a gait-specific manner. In addition, during FES-ambulation training, the lower limbs are guided through the gait cycle without the continuous assistance of therapists; therefore, it may be more clinically feasible. The purpose of this study was to investigate the effects of a 12-week FES-ambulation program on locomotor function and health-related quality of life (HRQOL) in individuals with AIS D SCI.

Methods

Participants

Six participants (3 males, 3 females; age 60.5 ± 13.2 years) with incomplete AIS D SCI (C4-L3; 9.3 ± 12.0 years post injury) were recruited from the Neuromuscular Rehabilitation Laboratory at Brock University. The participant pool for the current study was exclusive to individuals with AIS D SCI, because these individuals are most likely to experience locomotor improvements following ambulation therapy.[5] All participants were at least 1 year post injury. Exclusion criteria for the study included (a) participation in any FES-exercise of the lower limbs during the previous 3 months, (b) a history of heart disease or abnormal heart or lung sounds, (c) current pressure ulcers on the buttocks or the trunk, (d) a history of unpredictable and severe autonomic dysreflexia or orthostatic hypotension, (e) a history of fragility fractures, (f) drug or alcohol abuse, or (g) any musculoskeletal condition that would preclude exercise. In addition, none of the participants were involved in any formal gait training programs prior to the current investigation. All participants obtained medical clearance and performed an exercise stress test before enrolling into the study. Ethical approval was granted by the Brock University Research Ethics Board, and all participants gave their informed consent to participate in the study. Participant characteristics are provided in **Table 1**.

Exercise intervention

The exercise protocol consisted of 12 weeks of FES-ambulation, with the RT600 (Restorative Therapies, Baltimore, MD), at a frequency of 3 times per week. Before the start of each exercise session, gel electrodes were placed on the quadriceps, hamstrings, gluteus maximus, tibialis anterior, and both heads of the gastrocnemius. The electrodes were then connected to a stimulation cable that was, in turn, connected to a Sage box, which provided the electrical stimulation. A harness was placed around the participants' waist and was connected, with hook clips, to a motor-generated hoist. The participants were lifted off the ground with the hoist and then lowered onto the footplates of the RT600, where their feet were strapped in with Velcro straps. The footplates move separately in an elliptical motion to produce a gait-like cycle. The harness was then connected, via buckle straps, to the hoist to prevent excessive hip sway during the exercise. During the exercise, the RT600 ergometer moves the legs in an elliptical-like manner while the footplates alternate the ankles between dorsiflexion and plantar flexion, providing a walking-like pattern. Therefore, this form of gait training is not as gait specific as treadmill training; rather, it is a combination of elliptical and walking exercise.

Each exercise session began with a passive 2-minute warm-up as the legs were passively guided through the gait cycle with the motor of the RT600. Following the warm-up, electrical stimulation to the lower limbs was progressively increased as individually tolerated. The FES system was programmed to stimulate the muscles involved in each phase of the gait cycle at the appropriate time during stepping. Stimulation parameters included a pulse width of 300 μs and stimulation frequency of 35 Hz, and pulse amplitude varied between 5 and 60mA, depending on the muscle and the participant's comfort.

Exercise progression

Exercise duration, walking speed, and external body weight support (BWS) were gradually progressed throughout the 12-week exercise program in order to improve exercise performance. Specifically, participants were encouraged to walk 2 to 3 minutes longer over each successive session, and external BWS was progressively reduced as individually tolerated. In terms of walking speed, 4 of the 6 participants began and finished the exercise program at the maximum speed allowed by the RT600 (40 rpm). For the remaining 2 participants, walking speed began at 25 rpm and was progressively increased by 2 to 4 rpm per session, so long as the current amount of weight bearing could be maintained at that speed. Cessation of the exercise sessions occurred if the participants reached 1 hour of continuous exercise or if they reported that they were too fatigued to continue.

Outcome measures

Outcome measures were assessed 24 to 48 hours before the first exercise session (baseline testing) and again 48 to 72 hours after the last exercise session (post-testing). Post-testing occurred 48 to 72 hours after the last exercise session to ensure that any observed improvements were due to chronic adaptations rather than the acute effects of the last exercise session.

Locomotor function

The 6-minute walk test (6MWT) was used to measure walking endurance. If a participant was unable to walk continuously for 6 minutes, he or she was allowed to take breaks by either standing in place or sitting on a chair without stopping the timer. The 10-meter walk test (10MWT) was used to measure gait velocity (m/s). Participants were asked to walk as fast as they could, while maintaining balance and safety, for 10 m. The Walking Index for Spinal Cord Injury II (WISCI II) was used to measure walking independence.[15] The WISCI II is a 20-point scale test that measures walking independence based on the use of assistive devices. A score of 0 indicates that a person is unable to stand or participate in assisted walking, and a score of 20 indicates ambulation with no devices, no braces, and no physical assistance for 10 m. A researcher was always present during the overground walking tests to ensure safety and provide verbal encouragement. Furthermore, any assistive devices that were used during baseline testing for the 6MWT and the 10MWT were used again at the 12-week post-testing session.

Health-related quality of life

The Short Form-36 (SF-36) was used to assess changes in HRQOL,[16] as it is the most widely used and studied tool for the assessment of HRQOL.[17] The SF-36 is a self-administered, 36-item questionnaire that assesses 8 domains of perceived HRQOL during the previous 4 weeks; higher scores indicate better HRQOL. The Perceived Stress Scale (PSS) was used to measure changes in perceived stress levels.[18] The PSS is a self-administered, 10-item questionnaire that measures the amount of stressful situations experienced during the previous month. The PSS uses a 5-point scale where a score of 0 indicates that no stressful situations were experienced in the previous month and a score of 4 indicates that stressful situations were experienced very often. Thus, the higher the score, the more often stress was perceived. The Center of Epidemiological Studies for Depression scale (CES-D)[19] was used to measure depressive symptoms. The CES-D is a self-administered, 20-item questionnaire that assesses feeling states in the previous week. The CES-D uses a 4-point scale where a score of 0 indicates that depressive symptoms were rarely experienced and a score of 3 denotes that depressive symptoms were experienced most of the time. Thus, the higher the score, the more often depressive symptoms were experienced.

Statistical analysis

Due to the relatively small sample size and high amount of baseline variability between participants, outcome measures of pre and post testing were compared with nonparametric statistical analysis. Specifically, the Wilcoxon test was used to compare means at pre and post testing for the locomotor and HRQOL data. Spearman correlations were also performed to investigate possible relationships between locomotor outcome measures. All statistical analyses were performed with SPSS software (SPSS, Inc., Chicago, IL), and all data were expressed as means ± standard deviation (*SD*). Statistical significance was set at $P < .05$. Effect sizes (ES) for the locomotor and HRQOL data were also measured.

Results

Exercise adherence

Eight participants started the exercise program, however, 2 dropped out due to arthritic pain and excessive muscle tone that limited any kind of movement. Six participants successfully completed 12 weeks of FES-ambulation with an adherence rate of 84.7% ± 0.8%.

Exercise progression

After 12 weeks of FES-ambulation, the duration ambulated per session significantly increased (25.2 ± 5.7 min to 52.9 ± 9.7 min; $P = .01$) (**Figure 1**) and the required external BWS was significantly reduced (55.3% ± 12.6% to 14.7% ± 23.2%; $P = .03$) (**Figure 2**). There was no significant change in the speed of ambulation over the course of the training program (37.1 ± 4.2 rpm to 38.6 ± 2.5 rpm; $P = .10$), and this lack of improvement was likely due to a ceiling effect, as 4 of the 6 participants started and finished the exercise program at the maximum speed allowed by the RT600 (40 rpm).

Table 2. Locomotor outcomes before and after 12 weeks of FES-ambulation

	Pre test	Post test	*P*	Effect size
6-minute walk test (m)	223 ± 141.5	297.7 ± 164.5	**.03***	0.48
10-meter walk test (m/s)	0.69 ± 0.4	0.86 ± 0.5	.08	0.38
WISCI II	16 ± 4.3	17.7 ± 2.7	.06	0.46

Note: FES = functional electrical stimulation; WISCI II = Walking Index for Spinal Cord Injury II.
* Denotes significant improvement in the locomotor outcome measure after 12 weeks of FES-ambulation ($P < .05$).

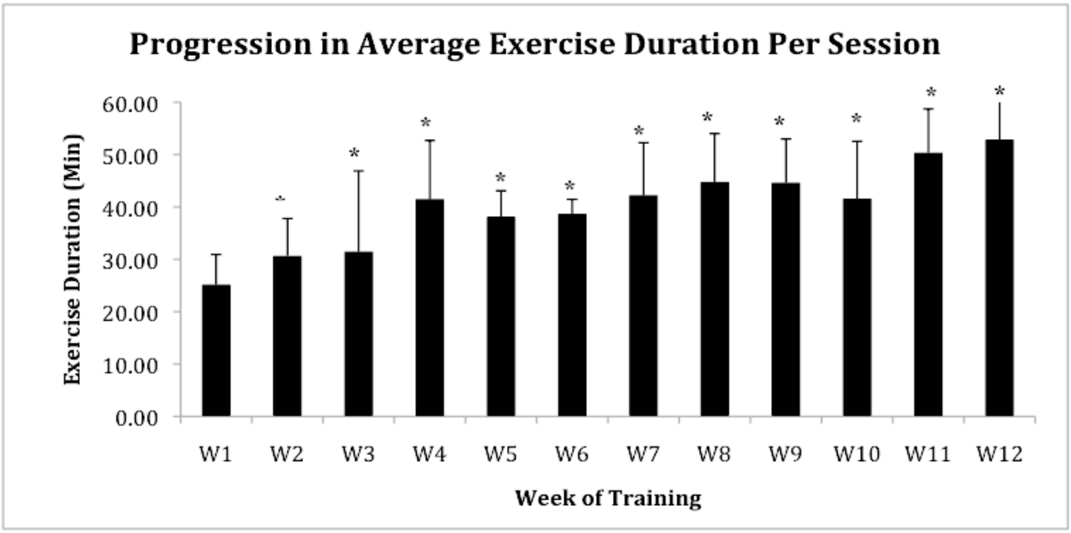

Figure 1. The progression in average exercise duration per session throughout 12 weeks of functional electrical stimulation (FES)-ambulation. *Denotes a significant increase in the average exercise duration per session compared to the first week of training ($P < .05$).

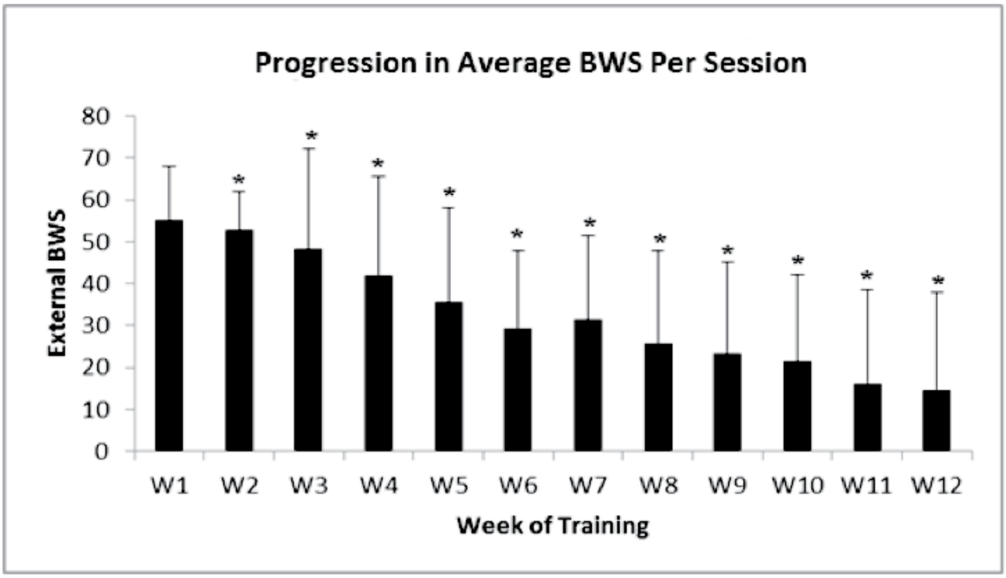

Figure 2. The progression in average external body weight support (BWS) required per session throughout 12 weeks of functional electrical stimulation (FES)-ambulation. *Denotes a significant decrease in the average external body weight support required per exercise session compared to the first week of training ($P < .05$).

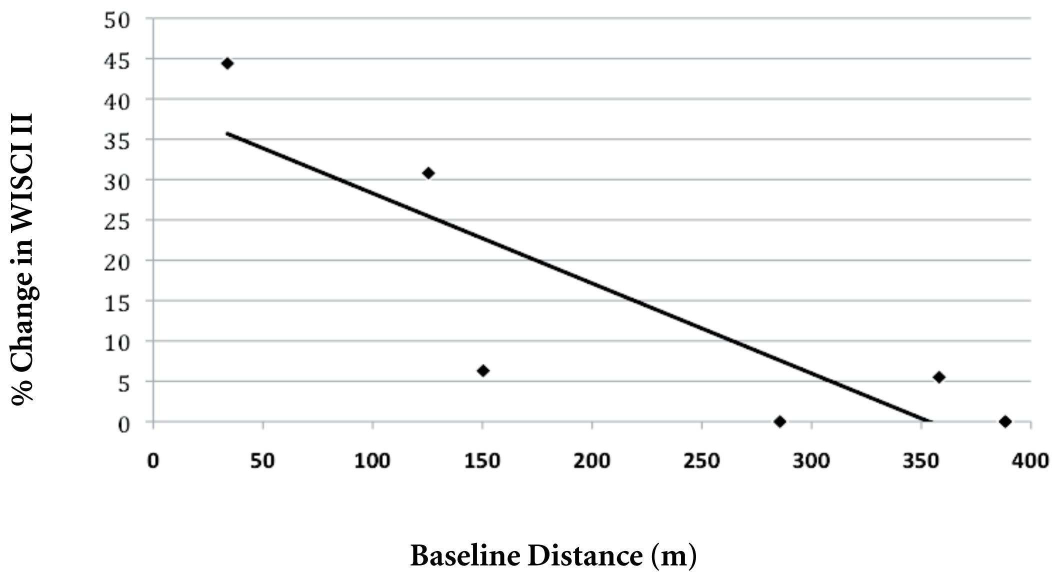

Figure 3. The correlation between baseline walking endurance (6-minute walk test) and the change in walking independence (Walking Index for Spinal Cord Injury II [WISCI II]) following training.

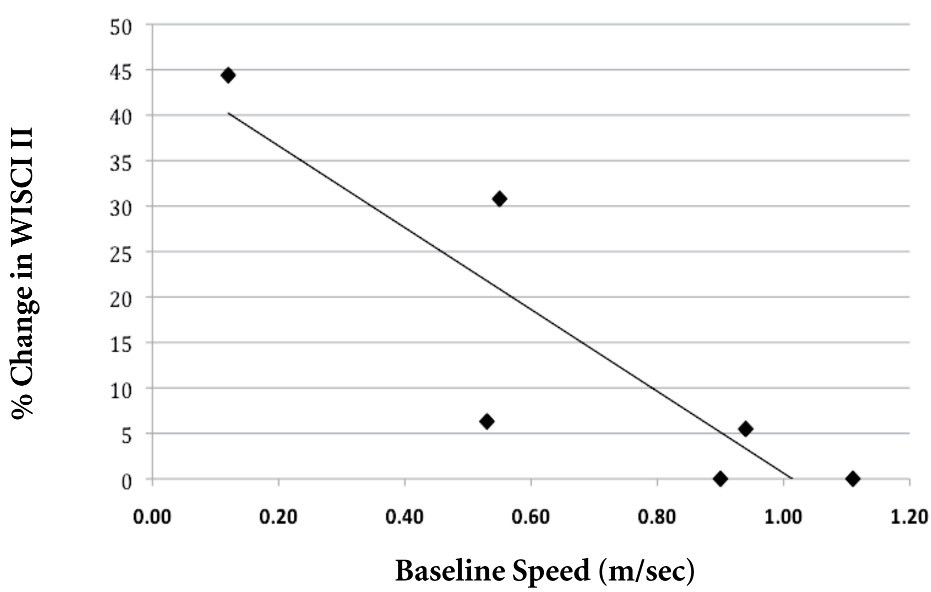

Figure 4. The correlation between baseline walking speed (10-meter walk test) and the change in walking independence (Walking Index for Spinal Cord Injury II [WISCI II]) following training.

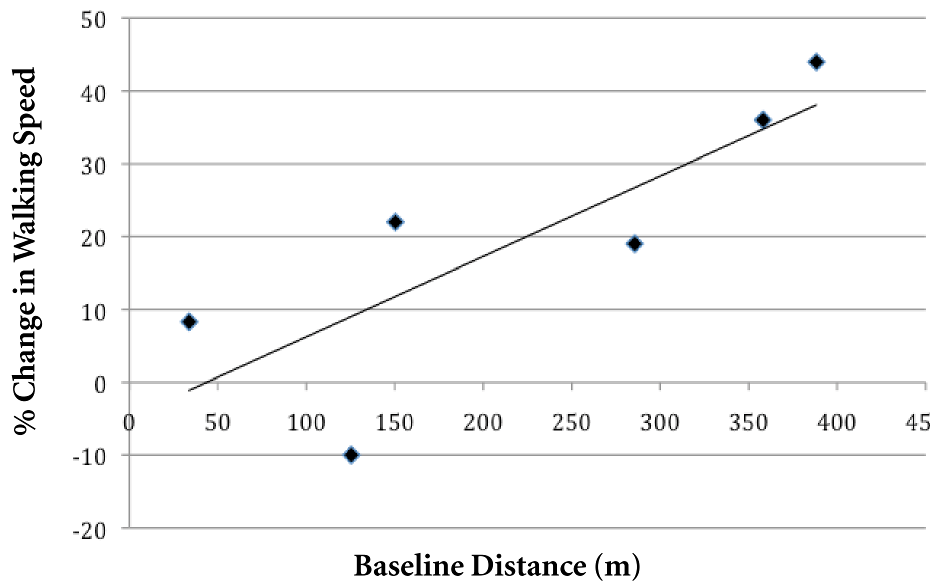

Figure 5. The correlation between baseline walking endurance (6-minute walk test) and the change in walking speed (10-meter walk test) following training.

Overground locomotor function

Following 12 weeks of FES-ambulation, participants experienced a significant increase in the distance walked during the 6MWT (223.6 ± 141.5 m to 297.3 ± 164.5 m; P = .03; ES = 0.48) and a trend toward an increase in walking speed during the 10MWT (0.69 ± 0.4 m/s to 0.86 ± 0.5 m/s; P = .08; ES = 0.38) and walking independence as determined by the WISCI II (16 ± 4.3 to 17.7 ± 2.7; P = .06; ES = 0.46) (**Table 2**).

A significant negative correlation was found between baseline walking endurance (6MWT scores) and the change in WISCI II scores (r = -0.90, P = .02) (**Figure 3**), as well as baseline walking speed (10MWT scores) and changes in the WISCI II scores (r = -0.84, P = .04) (**Figure 4**). These results indicate that participants with the lowest baseline overground walking function (endurance and speed) experienced the greatest amount of improvement in walking independence. There was also a significant positive correlation between baseline walking endurance and changes in walking speed (r = 0.89, P = .02) (**Figure 5**), suggesting that those with the highest baseline endurance experienced the greatest amount of improvement in walking speed.

Health-related quality of life

Twelve weeks of FES-ambulation were associated with a significant reduction in bodily pain (6.5 ± 1.2 to 5.0 ± 1.7; P = .04; ES = 1.09) and an increase in overall mental health (47.8 ± 12.6 to 54.2 ± 6.7; P = .04; ES = 0.60) (**Table 3**), as determined by the SF-36. However, no significant changes were detected in perceived stress or depression (**Table 4**).

Discussion

The main findings of the current study are that 12 weeks of FES-ambulation improved overground walking endurance, reduced pain, and improved overall mental health in individuals with AIS D SCI. The data also revealed strong trends for improved overground walking speed and independence after the 12-week training program. However, the effect sizes for these changes were fairly small, and further research is required to

Table 3. Short Form-36 scores before and after 12 weeks of FES-ambulation

	Pre test	Post test	P	Effect size
Physical function	17.5 ± 6.9	16.5 ± 4.8	.76	0.16
Role-physical	6.0 ± 1.9	5.5 ± 1.4	.49	0.23
Body pain	6.5 ± 1.2	5.0 ± 1.7	.04*	1.02
General health	18.5 ± 3.3	20.2 ± 3.6	.57	1.02
Overall physical component	49.5 ± 9.4	50.2 ± 6.5	.6	0.09
Vitality	13.7 ± 4.3	15.5 ± 2.8	.16	0.50
Social function	6.0 ± 2.0	7.2 ± 1.7	.18	0.65
Role-emotional	5.0 ± 1.3	5.2 ± 1.2	.79	0.16
Mental health	23.2 ± 5.8	24.7 ± 2.7	.37	0.33
Overall mental component	47.8 ± 12.6	54.2 ± 6.7	.04*	0.63

Note: FES = functional electrical stimulation.

* Denotes significant improvement in the health-related quality of life subcomponent after 12 weeks of FES-ambulation ($P < .05$).

determine whether these variables are also prone to improve after FES-ambulation training.

Locomotor function

In the last decade, several methods of ambulation training have been extensively examined in individuals with incomplete SCI. These methods include traditional BWSTT,[3,4,5,6,7] automated treadmill training,[11,20] overground walking,[3] and electrically stimulated ambulation.[21,22] FES-ambulation with the RT600 is one of the latest forms of ambulation training to join this group of rehabilitative techniques. FES-ambulation has been tested in individuals with incomplete SCI; however, in these studies either the common peroneal nerve was the only nerve stimulated during walking[3,22] or multiple muscles were activated, but participants had to actively trigger the FES during the initiation of the gait cycle while ambulating on a treadmill.[21] In contrast, the current exercise protocol provided FES to many of the major muscles of the lower limbs (quadriceps, hamstrings, gluteus maximus, tibialis anterior, and both heads of the gastrocnemius), and the FES was continuously and automatically synchronized with the gait cycle, which allowed the participants to focus on their walking rather than controlling the stimulation cycle. Although all of the participants in the current study had AIS D injuries and were somewhat ambulatory before training, FES to the lower limbs was a critical component of the exercise as the voluntary contribution over the course of each session seemed to decrease due to muscle fatigue. At that point, we hypothesize that the FES assisted with timing and coordination of muscle firing. Otherwise, before fatigue, the FES was likely used to maximize muscle contractions in order to improve muscle strength.

Although FES-ambulation training was associated with improved locomotor function, direct comparison to other ambulation training studies is difficult due to methodological differences, such as time post injury, level and severity of injury, and the training parameters used. The Spinal Cord Injury Locomotor Trial examined the effects of 12 weeks of ambulation training on locomotor function in individuals with acute incomplete SCI.[7] At baseline, participants with AIS C and D SCI had no measurable overground walking speed or distance. Following 12 weeks of BWSTT, however, overground walking speed improved

Table 4. Perceived stress and depression before and after 12 weeks of FES-ambulation

	Pre test	Post test	P	Effect size
PSS	15.5 ± 8.5	13.5 ± 5.1	.4	0.29
CES-D	13.5 ± 12.8	11.2 ± 5.9	.9	0.23

Note: CES-D = Center of Epidemiological Studies for Depression scale; FES = functional electrical stimulation; PSS = Perceived Stress Scale.

to 0.85 m/s and participants walked 247.7 m during the 6MWT. Although overground walking function improved significantly, participants were in the acute stage of the injury, as they were recruited within the first 8 weeks of the SCI. Thus, the reported improvements in overground walking were likely due to a combination of spontaneous recovery and the ambulation training, rather than the training program alone. Accordingly, the authors also demonstrated that greater locomotor improvements were exhibited by the individuals who began their training more recently following the injury. As a more relevant comparison, Hicks et al[4] examined the effects of 12 months of BWSTT in individuals with chronic incomplete SCI, with all participants being at least 1 year post injury. In that study, large and robust improvements were noted for walking speed and distance while participants were on the treadmill (180% and 335%, respectively), but only 5 out of 14 participants improved their overground walking independence. Direct comparisons are difficult to make, as overground walking was measured with the Modified Wernig scale, which is not validated and may not be sensitive enough to detect even moderate changes in walking speed and distance. Furthermore, automated locomotor training with the Lokomat has also been shown to improve overground walking function in individuals with chronic incomplete SCI. Specifically, results from Wirz et al[20] showed that 8 weeks of Lokomat training increased overground walking speed and endurance by 56% and 53%, respectively. However, regarding walking independence, these authors showed that only 2 out of 20 participants improved their WISCI II scores (range, 1-3) following this 8-week Lokomat trial. This limited improvement in walking independence was also seen in results from Thrasher et al[21] who reported that only 1 participant improved in walking independence following 12 weeks of BWSTT combined with FES. According to these results, and our own, it is tempting to state that FES-ambulation training with the RT600 may be comparable to other forms of ambulation training; however, due to the different sample sizes, levels of injury, and baseline presentations, this conclusion should be considered with caution. Further research on FES-ambulation with larger sample sizes and varying levels and severities of injury is certainly warranted, as our findings do show promise for this form of rehabilitation.

Regarding the importance of training specificity, it bears repeating that FES-ambulation training with the RT600 uses leg motion that is more similar to elliptical training than treadmill training, except that the stimulation also evokes dorsiflexion and plantar flexion similar to a gait pattern. As such, this form of training lies somewhere between elliptical exercise and walking in terms of its specificity. Although other forms of gait training, such as manual locomotor training and the Lokomat, may be more walking specific, the results from the current investigation show comparable overground walking benefits. Thus, the gait pattern produced by the RT600 may be specific enough to realize locomotor benefits; alternatively, where this training stimulus falls short in terms of specificity, it makes up for by maximizing muscle contractions during the exercise. Still, regardless of the exact parameters responsible for the locomotor benefits, it is noteworthy that all participants in the current study experienced significant improvements in the requirement of BWS on the RT600 and overground walking endurance post training. This may have been due to the specificity of training parameters, as both walking duration and external BWS were gradually progressed throughout the exercise program for all participants. The speed of ambulation during the training sessions was not as uniformly progressed over the 12 weeks, as 4 of the 6 participants started and finished the training program at the maximum allowed speed of the RT600. Accordingly, changes in overground walking speed following the 12-week program did not reach statistical significance. Thus, specificity of training appears to be an important consideration with FES-ambulation training and further studies are warranted in order to develop optimal training dosages and parameters to improve locomotor function. Overground walking is likely the most specific form of ambulation training, and a recent randomized control trial has shown it to result in greater locomotor improvements compared to treadmill-based training.[3] However, one of the criticisms that overground ambulation training has received is that it may be limited to individuals with paraplegia, as trunk control and upper extremity strength are required to use the assistive devices that are often necessary.[23] Still, given the small sample size of the current study and the novelty of this form of training, further larger scale investigations are warranted to determine the effects of FES-ambulation training with the RT600 and the importance of training specificity with this device.

The correlations in the current study should be considered with caution given that they were drawn from only 6 participants. The correlations suggest that individuals with less overground walking function may experience greater improvements in walking independence with FES-ambulation compared to those with more preserved function. However, this may be due to the fact that individuals with less function have more room for improvement. In addition, the correlations also suggest that more able participants may improve more in walking speed compared to those with less function. This observation is in contrast to previous studies that have shown higher baseline function to be a predictor of greater walking improvement following ambulation training.[4] Still, the results from the current study lead us to speculate that locomotor recovery, at least with FES-ambulation, likely begins with gross motor improvements and is followed by fine tuning in gait patterns and increases in walking speed. However, further research is required to verify this hypothesis. In contrast, however, Wirz et al[20] showed that slower ambulators at baseline exhibited the greatest amount of improvement in walking speed, while those with the lowest baseline walking endurance improved the most in walking endurance.

Health-related quality of life

To date, the effects of ambulation training on QOL after SCI have not been extensively examined. The current study showed that 12 weeks of FES-ambulation resulted in a reduction in perceived bodily pain and an increase in overall mental health. Improvements in bodily pain agree with findings from Martin Ginis and Latimer[9] who reported that a single bout of BWSTT may reduce perceived pain, which consequently improves feeling states in individuals with incomplete SCI. Hicks et al[4] have shown that 12 months of BWSTT increased perceived physical function and improved life satisfaction in individuals with incomplete SCI. In contrast, a case series of 3 individuals has shown that 12 weeks of BWSTT resulted in small and diverse changes to QOL.[8]

An unexpected finding in the current study was that neither stress nor depression levels decreased after the exercise program. Several studies have shown exercise to be an effective means for decreasing stress and depression levels after SCI.[24-26] Moreover, Latimer et al[26] have shown that exercise-induced reductions in pain mediate the reduction in stress levels, which in turn mediate a decrease in depressive symptoms after SCI.

Limitations

The main limitation in the current study was the small number of participants and the lack of a nonexercising control group. However, despite the small sample, only individuals with AIS D injuries were included, and therefore the participants were relatively homogeneous. In addition, all participants were at least 1 year post injury (range, 1-19 years), and, thus, the improvements in ambulation and QOL were very likely exercise-induced rather than spontaneous recovery. However, due to the lack of a control group using an alternate form of locomotor therapy, it is unclear whether or not our participants would have experienced the same benefits in overground walking with any form of ambulation training. Again, further research is required to determine the relative effectiveness of FES-ambulation training compared to other existing forms of locomotor therapy. Another limitation was the possible ceiling effect that likely occurred for our measures of walking independence. Specifically, 2 of the 6 participants in this study had perfect baseline WISCI II scores; thus, any further improvements in walking independence that they may have achieved could not have been reflected by their post-testing scores. The effects of FES-ambulation on walking independence were likely underestimated in this study, especially considering that the 2 participants with perfect baseline WISCI II scores did improve in walking speed and endurance after the 12-week training program. The training intensity offered by the RT600 was partially limited due to the maximal cadence of 40 rpm, and this was another possible limitation to the study. However, the ceiling of 40 rpm did not likely limit gains in independence or endurance, as no correlations were found between changes in training speed and these indices of overground walking performance. Still, the participants may have exhibited significant improvements in overground walking speed if the training intensity could have been increased above 40 rpm. Further research and possible modifications to the RT600 would be required to test this hypothesis. The final limitation of the current study was the wide range of FES intensities used. Two of the participants experienced hypersensitivity with FES, and therefore extremely low stimulation intensities were used for these participants. Accordingly, with such low stimulation intensities, weak functional contractions were generated by the muscles, which may have reduced the effectiveness of the intervention.

Conclusion

The current study suggests that 12 weeks of FES-ambulation training may be an effective means for enhancing overground walking function in individuals with incomplete SCI. In addition, it appears to also be effective in reducing bodily pain and improving mental health in individuals with incomplete SCI.

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